A NOMA Scheme for Visible Light Communications with Single Carrier Transmission and Frequency-Domain Successive Interference Cancellation

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Abstract

We propose a non-orthogonal multiple access (NOMA) scheme for visible light communications (VLC) based on single carrier (SC) transmission and frequency-domain successive interference cancellation. The scheme can achieve low peak-to-average power ratio (PAPR), a good balance between throughput and fairness, and a higher system capacity for a larger number of users. We show by experiment that SC with a lower PAPR offers improved bit error rate (BER) performance compared with the orthogonal frequency division multiplexing.

Key words

visible light communications (VLC), non-orthogonal multiple access (NOMA), single carrier transmission.

1. Introduction

Visible light communications (VLC) is gaining great interest in both wireless and optical community, due to the advantages of license-free, high confidentiality and low-cost [1-3]. Similar to other wireless communication technologies, multiple access techniques are crucial in VLC to support multiple services to multiple users concurrently. Orthogonal multiple access (OMA) techniques such as time domain multiple access (TDMA), orthogonal frequency domain multiple access (OFDMA) and interleaved frequency division multiple access (IFDMA) have been introduced into VLC [4-7]. However, they suffer from the tradeoff between throughput and fairness.

Recently, non-orthogonal multiple access (NOMA), a novel multiple access strategy, has drawn great attention [8-10]. Unlike the conventional multiple access technologies, NOMA superposes user data in the power domain and uses successive interference cancellation (SIC) at the receiver (Rx) to separate the user data, so that all of the users can use the whole time-frequency resources. As a result, NOMA can balance throughput and fairness. It has been regarded as a promising solution to enhance the spectral efficiency for the 5th generation (5G) wireless networks [8-10].With good feasibility and performance, it has also been adopted for VLC systems [11-13].In [14], a phase pre-distortion method was proposed to improve the symbol error rate performance of NOMA uplink with SIC decoding in VLC. In [15], we propose a NOMA scheme combined with OFDMA for VLC, which offers flexible bandwidth allocation and a higher system capacity.

In this paper, we propose a NOMA scheme for VLC system with single carrier (SC) format and novel frequency domain SIC (FD-SIC). SC transmission can outperform OFDM in terms of peak to average power ratio (PAPR), which is critical to VLC system due to the high nonlinearity of LED [16]. The feasibility of the NOMA-VLC with SC transmission is verified by experiment. The effect of power allocation ratio (PAR) on the bit error rate (BER) performance is investigated. As shown in the experiment results, compared with OFDM, the SC transmission for NOMA-VLC offers better BER performance for both downlink and uplink.

The rest of the paper is organized as follows. In section II, we introduce the SC NOMA scheme with FD-SIC for VLC systems. Section III presents the experiment setup and results followed by the concluding remarks in Section IV.

2. Technique principle

Figure 1 shows the schematic diagram of proposed NOMA-VLC with N users and FD-SIC. At the transmitter (Tx), the source data for each user is mapped and grouped into blocks prior to power allocation, respectively. Cyclic prefix (CP) is added in the front of each block to combat the multi-path induced inter-symbol interference. Preamble is added in the front of each frame for the purpose of frame synchronization and channel estimation. Then all the transmitted signals are combined with a total transmitted power of P, which can be given by:

$$x = \sum_{i=1}^{N} \sqrt{p_i} x_i, \tag{1}$$

where p_i and x_i are the allocated power and the transmitted time-domain signal for user i, respectively. Note that the power allocation is realized in the digital domain and optical domain for downlink and uplink, respectively. At the Rx, the received signal can be written as:

$$y = \sum_{i=1}^{N} h_i \otimes x_i + \mathrm{w}, \tag{2}$$

the frequency-domain representation of which can be written as:

$$Y = \sum_{i=1}^{N} H_i \times X_i + W\ , \tag{3}$$

where h_i and H_i are time-domain and frequency-domain channel coefficients for user i respectively, which can be calculated from the inserted time-multiplexed training sequences in the preambles respectively. We assume the user with a lower index is allocated with more power than that with a higher index, so that $H_1 > H_2 \ldots > H_N$. The received signal is passed through a frame synchronization module prior to CP removal. In the proposed FD-SIC, after discrete Fourier transform (DFT) operation, the received signal for user 1 can be obtained from dividing Y by H_1, which can be written as:

$$Y_1 = X_1 + \sum_{i=2}^{N} \frac{H_i}{H_1} X_i + \frac{W}{H_1}. \tag{4}$$

The transmitted signal of user 1 (i.e., s_1) is recovered after demapping the time domain representation of Y_1. After removing the term of $H_1 X_1$ in (3), the received signal is divided by H_2, which can be given by:

$$Y_2 = X_2 + \sum_{i=3}^{N} \frac{H_i}{H_2} X_i + \frac{W}{H_2}. \tag{5}$$

The transmitted signal of user 2 (i.e., s_2) can be recovered after demapping the time domain representation of Y_2. The decoding order of FD-SIC is in the order of increasing channel gain (i.e., H_i). Finally, the received signal for user N can be written as:

$$Y_N = X_N + \frac{W}{H_N}. \tag{6}$$

After demapping the time domain representation of Y_N, the transmitted signal for user N is obtained without inter-user interference.

3. Experimental setup and results

Figure 2 shows the experimental setup for NOMA-VLC with two users. In the downlink, two 1.7-Mbaud baseband 4-quadrature amplitude modulation (QAM) signals are three times up-sampled and then up-converted to 1.25 MHz by means of digital I-Q modulation. This ensures the generated SC signals are real-valued, which can be used for IM of the LED. The two generated signals are combined after power allcation in the digital domain and then uploaded to an arbitrary waveform generator (AWG) operating at 5 MS/s. The block size and CP length are 256 and 8, respectively. The generated waveform is converted into analog streams and then superimposed onto a direct current (DC) via a bias Tee to drive the commercially available phosphorescent white LED. At the Rx, a commercial optical Rx (THORLABS PDA36A) is used to convert the optical signal to the electrical signal. To simplify the experiment, no lens is utilized to concentrate light. The electrical signal is captured by a real-time digital oscilloscope. After frame synchronization and down conversion, the transmitted data for each user is decoded as shown in Fig. 1 (b). For comparison, we have also investigated an OFDM-based NOMA VLC with two users. The parameters of which is the same as that for NOMA-VLC with signal carrier transmission. All the key system parameters are provided in Table 1.

Figure 3 shows the bit error rate (BER) as a function of the distance between the transmitter and receiver. The PAR between the two users is set to 0.16, 0.25 and 0.36, respectively. Each BER is calculated from the average of the two users, which is based on more than 1×10^6 bits. As shown in Fig. 3, the optimal BER performance is achieved with a PAR of 0.25. Figure 4 shows the BER performance of the two users with OFDM and SC modulations with a PAR of 0.25. At the Tx, user 1 is allocated with more power. At the Rx, the data of user 1 is decoded prior to decoding the data of user 2. If the data demodulation of user 1 cannot be accurately realized, the data of user 2 cannot be recovered with error-free operation. As such, the BER performance of user 1 is better than that of user 2. The constellations are captured under a transmission span of 17.5 cm. Due to interference from user 2, the constellation of user 1 looks like 16 QAM constellation. As shown in Fig. 4, SC transmission offers better BER performance due to its low PAPR.

The experimental setup for uplink NOMA- VLC with two users is shown in Fig. 5. The two SC signals are generated and uploaded into two AWGs respectively. The outputs of the AWGs are converted into analog streams and then DC-level shifted using the bias Tee prior to IM of two commercially available phosphorescent white LEDs, respectively. The distance between Tx and Rx and the distance between users are set to 15 cm and 10 cm, respectively. The PAR between the two users depends on the position of the Rx. In order to allocate more power to user 1, the Rx should be placed at the point with an x coordinate less than 5 cm. At the Rx, the optical signals are detected by a photo detector and then captured by the scope. The captured signal is decoded in the Matlab. OFDM based NOMA-VLC experiment is also carried out here for comparison. The system parameters are similar to that for downlink. The difference between uplink and downlink is the power allocation method employed. In the downlink, the power allocation is realized in the digital domain, while it is in the optical domain for uplink.

Figure 6 shows the average BER performance for uplink NOMA-VLC based on SC and OFDM modulation. The position of the Rx is changed in the x-direction within the range of -6 to 4 cm. So that user 1 is allocated with more optical power. The data of user 1 is decoded prior to decoding the data of user 2. With the increase of x coordinate value, the PAR between the two users increases. As shown in Fig. 6, the best BER performance is achieved with the Rx being placed at the point with an x coordinate of 2 cm for both SC and OFDM. Due to its low PAPR, NOMA-VLC with SC performs better than OFDM, which is similar to the case of downlink transmission.

3. Conclusion

We proposed and experimentally demonstrated a NOMA scheme based on single carrier transmission and frequency domain inter-user interference cancellation for VLC. The power allocations were realized in digital and optical domain for downlink and uplink, respectively. Compared with NOMA-VLC with OFDM modulation, our proposed scheme offered better BER performance, due to its low PAPR.

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TABLE I. SYSTEM PARAMETERS

Parameter	Value
LED	
• Bandwidth	< 5 MHz
• Semi-angle of half power	~ 60^o
• Transmit power	150 mw
Pin photodetector	
• Active area A_r	13 mm^2
• Responsivity R	< 0.4 A/W
• Bandwidth	10 MHz
• Field of view of Receiver	~90^o
OFDM and Single Carrier	
• No. of user	2
• RF carrier	1.25 MHz
• Modulation format	4-QAM
• DFT size	256
• CP size	8

Figures

Fig. 1 Block diagrams for (a) NOMA coder (b) NOMA decoder (CP: cyclic prefix, CE: channel equalization, DFT: discrete Fourier transform, IDFT: inverse discrete Fourier transform).

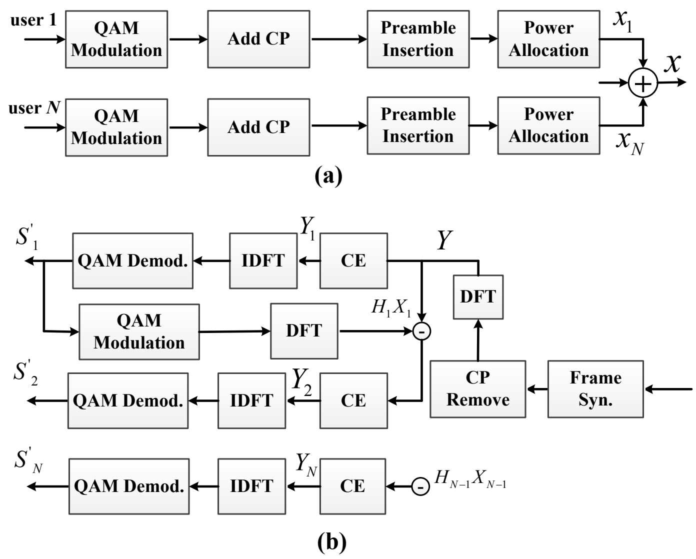


Fig. 2 Experiment setup for downlink NOMA-VLC.

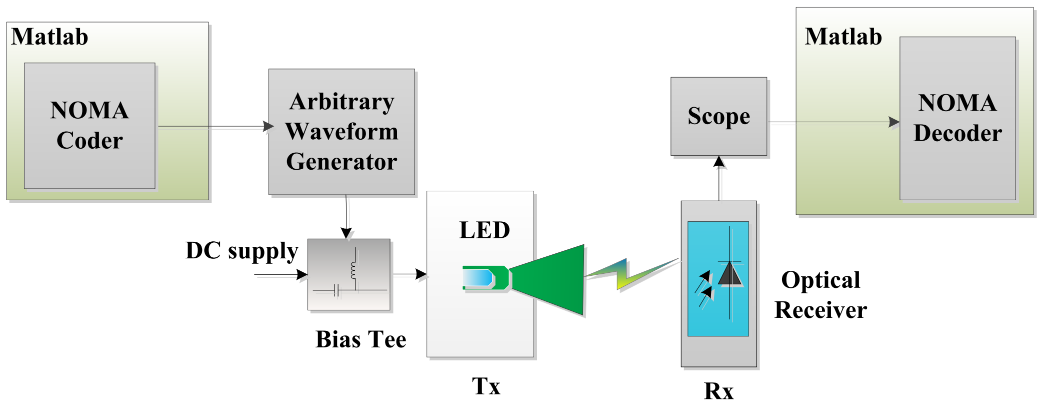


Fig. 3 The optimum PAR for downlink NOMA-VLC.

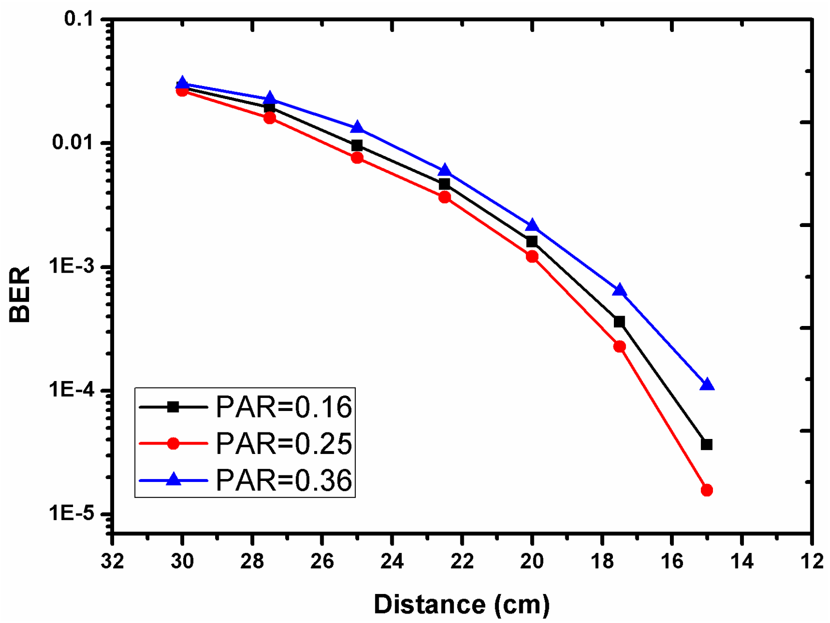


Fig. 4 Downlink BER performance for SC and OFDM with a PAR of 0.25.

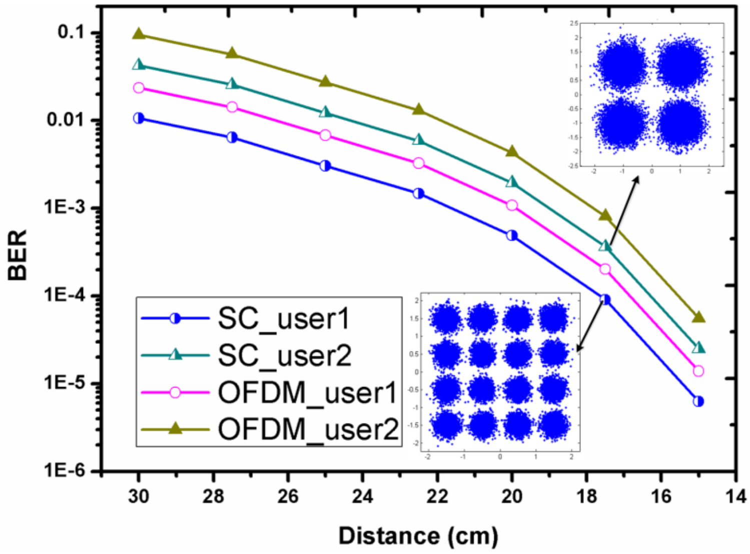


Fig. 5 Experimental setup for uplink NOMA- VLC.

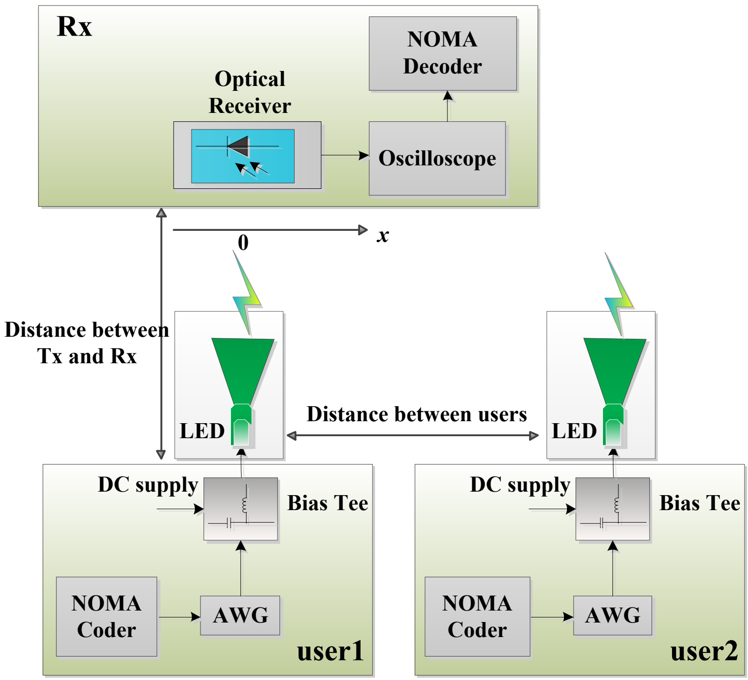
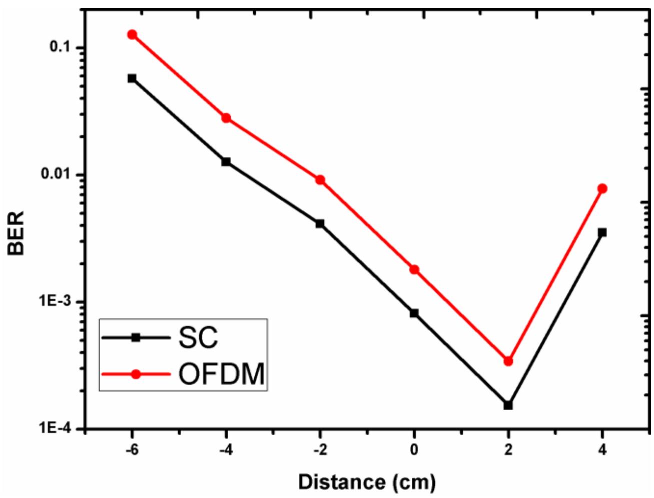


Fig. 6 Average BER performance for uplink NOMA-VLC.



0.1
0.01
1E-3
1E-4
BER
-6
-4
-2
0
2
4
Distance (cm)
SC
OFDM